

IN-SITU RESOURCE UTILIZATION IN THE DESIGN OF ADVANCED LUNAR FACILITIES

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Resource utilization will play an important role in the establishment and support of a permanently manned lunar base. At the University of Houston - College of Architecture and the Sasakawa International Center for Space Architecture, a study team recently investigated the potential use of lunar *in-situ* materials in the design of lunar facilities. The team identified seven potential lunar construction materials: concrete, sulfur concrete, cast basalt, sintered basalt, glass, fiberglass, and metals. Analysis and evaluation of these materials with respect to their physical properties, processes, energy requirements, resource efficiency, and overall advantages and disadvantages lead to the selection of basalt materials as the more likely construction material for initial use on a lunar base. Basalt materials can be formed out of *in-situ* lunar regolith, with minor material beneficiation, by a simple process of heating and controlled cooling. The team then conceptualized a construction system that combines lunar regolith sintering and casting to make pressurized structures out of lunar resources. The design uses a machine that simultaneously excavates and sinters the lunar regolith to create a cylindrical hole, which is then enclosed with cast basalt slabs, allowing the volume to be pressurized for use as a living or work environment. Cylinder depths of up to 4-6 m in the lunar mare or 10-12 m in the lunar highlands are possible. Advantages of this construction system include maximum resource utilization, relatively large habitable volumes, interior flexibility, and minimal construction equipment needs. Conclusions of this study indicate that there is significant potential for the use of basalt, a lunar resource derived construction material, as a low cost alternative to Earth-based materials. It remains to be determined when in lunar base phasing this construction method should be implemented.

INTRODUCTION

With the announcement of President Bush's plan to return man to the Moon permanently, it will be important to identify new and innovative technologies that will insure the success, sustainability, and eventual growth of a lunar base. Many of these technologies involve the use of lunar resources. Lunar resources can be used to supply needed replenishables for a lunar base, replenishables that would otherwise have to be brought from Earth, a more costly alternative. Lunar resources contain abundant supplies of oxygen for life support systems and rocket propellant, and less abundant but significant supplies of volatile gases. Additionally, lunar resources can be used to supply construction materials for the growth of a lunar base. The use of lunar-derived construction materials will be one of the most significant steps toward self-sufficiency and independence from terrestrial resources.

In view of this important step, research at the University of Houston-College of Architecture and Sasakawa International Center for Space Architecture has been undertaken to identify and analyze potential lunar-derived construction materials, and apply the findings to the design of an advanced lunar facility. This paper presents a summary of these findings and a summary of the final design concept that was developed as a NASA/USRA advanced design project.

Project Goals

The four primary goals of this project are:

- To develop a structural system using products derived from lunar resources;
- To design pressurized and unpressurized structures that exploit the use of lunar resources;

- To discover economical and practical uses for lunar resources in support of lunar structures; and
- To establish self-sufficiency and independence from terrestrial resources.

Project Assumptions

In general, it is assumed that the use of lunar-derived construction materials would begin at an advanced phase of a lunar base, not at its initial phase. Because of the dynamic character of lunar base planning at present, the design team chose not to assume any single scenario, preferring instead to concentrate on the development and organization of a structural system that is both functionally flexible and adaptable to many lunar base scenarios.

LUNAR RESOURCES

Of the potential resources, the lunar regolith is the most accessible and easily converted into lunar construction materials. It is, on average, 80 μm in diameter, and contains oxygen, silicon, magnesium, iron, calcium, aluminum, and titanium as its seven primary elements⁽¹⁾. It can be divided into two groups, the mare basalts and the anorthositic highland rocks. The mare basalts are relatively higher in iron, magnesium, and titanium content, and have a surface depth between 4 to 6 m. The anorthositic highland rocks are relatively higher in aluminum and calcium content, and have a surface depth between 10 to 12 m. Figure 1 shows the average elemental compositions of lunar surface regolith for both the mare and the highlands.

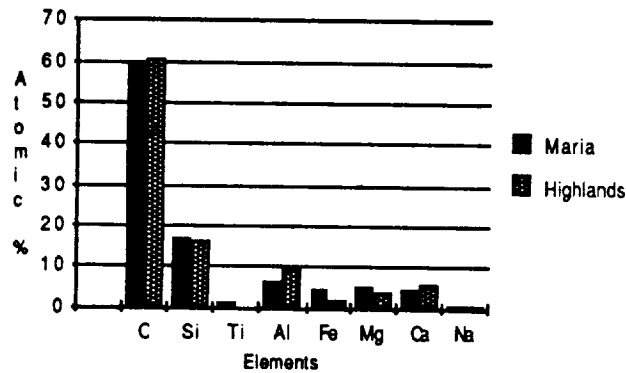


Fig. 1. Average Elemental Compositions of Lunar Surface Regolith

CONSTRUCTION MATERIALS

The research team identified seven possible construction materials that can be derived from lunar resources. These materials include two varieties of basalt, cast and sintered; two varieties of glass, cast and fiber; concrete; sulfur-based concrete; and metals. Each construction material was evaluated on criteria that included physical properties, production processes, energy requirements, material resource yields, products, applications, and miscellaneous requirements of the material such as dependence on terrestrial resources. A very brief overview of each construction material is given below.

Basalt

Basalt can be formed in two different ways, casting, a process by which regolith is heated until molten, poured into molds, and then cooled in a slow, controlled manner, and sintering, a process by which regolith is heated under pressure (below the melting point), causing the regolith material to bind together. Basalts, in general, have high compressive strengths, involve simple processing techniques, are resistant to chemicals and abrasion, have good resource yields, and are easily cast. Disadvantages of basalt include its brittleness, low tensile strength, and the need for metal molds in precision casting.

Glass

Glass can be cast into blocks and panels, or it can be spun into fibers. The primary difference between glass and basalt

processing is that the cooling rate of glass is much higher. Glass, when manufactured in the anhydrous vacuum conditions of the lunar environment, attains extremely high compressive and tensile strengths. Unfortunately, it loses much of its strength when exposed to air, has very high energy requirements for processing, is very brittle, and requires organic bonding agents when produced as fiberglass.

Concrete

Lunar concrete is very similar to Portland cement concrete used here on Earth. Advantages of this construction material include its relatively simple production, low energy requirements, high abrasion resistance, and easy castability. The major disadvantage of lunar concrete is that it requires water, or in the case of lunar oxygen production, hydrogen to be supplied from the Earth. Additional disadvantages include its low tensile strength, long curing time, and the requirement of pressurized processing.

Sulfur-based Concrete

As the name implies, sulfur-based concrete uses sulfur as the binding agent. Advantages include its high early strength, resistance to corrosion, and its independence from terrestrial resources. Disadvantages include material deterioration at lunar daytime temperatures, low sulfur yields from the lunar regolith, and flammability of the sulfur.

Metals

As was shown earlier, a number of metals exist in the lunar regolith including iron, magnesium, aluminum, and titanium. These metals, because of their high tensile and compressive strengths and their ability to be formed into small, intricate parts, would be ideal for construction materials for lunar applications. Unfortunately, extraction of metals on the Moon is an extremely complicated and high energy process, with relatively low yields. Only if metal extraction were linked with another process, such as the reduction of ilmenite for oxygen, would the process approach effectiveness.

Table 1 shows the physical properties of candidate construction materials. Iron was chosen as a representative metal because it is easier to extract than other metals and, therefore, a more likely candidate for a lunar construction material.

Figure 2 presents a summary of candidate construction materials. Each material was given grades for processing

Table 1. Physical Properties

	Glass	Basalt	Concrete	Sulfur Con.	Iron
Compressive Strength (MPa)	620	540	76	55	—
Tensile Strength (MPa)	3000	35	—	7.1	270
Modulus of Elasticity (GPa)	870	110	21	—	196
Density (g/cm ³)	2.7	2.9	2.4	2.4	7.8
Melting point (°C)	1500	1300	600	115	1537
Cooling point (°C)	760	800	—	—	—
Thermal Expansion (cm/cm°C)	4.2×10^{-6}	7.8×10^{-7}	1.19×10^{-5}	1.44×10^{-5}	1.2×10^{-5}

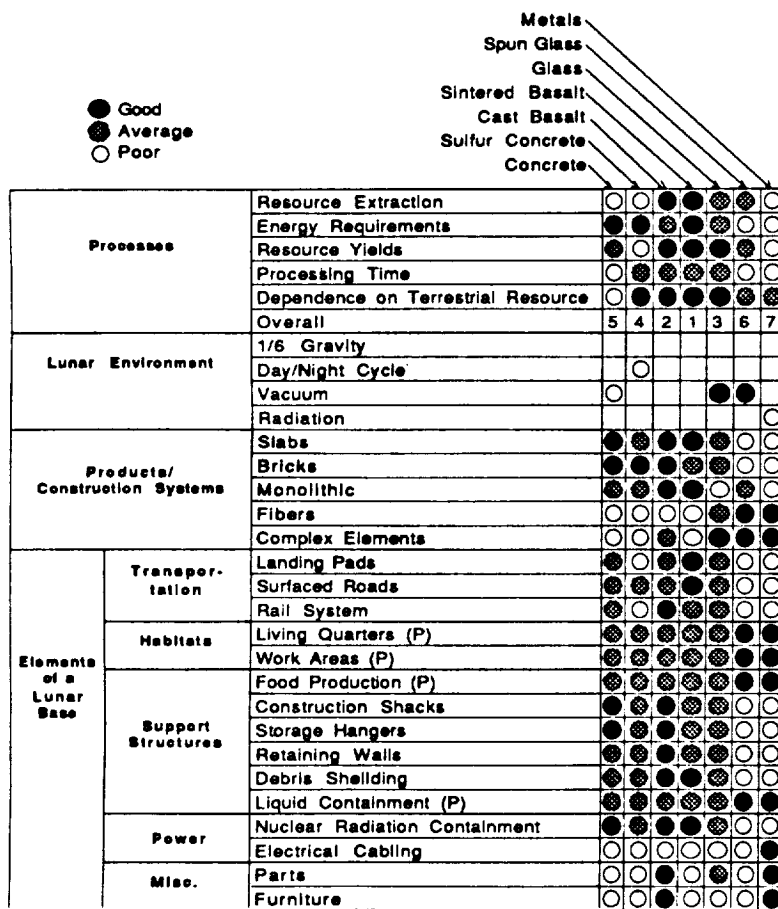


Fig. 2. Material Summary

according to characteristics of resource extraction, energy requirements, resource yield efficiency, processing time, and dependence on terrestrial resources. An overall process ranking was then given to each construction material. Effects of the lunar environment on each construction material were positively or negatively noted, and possible products were identified. Finally, applications of each construction material were evaluated according to various elements of a lunar base. Thus, it was easy to identify the construction material or materials that would meet the goals of the project and would be more appropriate for initial use on a lunar base.

Basalt materials were chosen for use on this project because of their high yield efficiency, simple process, short processing time, independence from terrestrial resources, variety of potential products and applications, and the lack of negative lunar environment effects.

DESIGN

The design of a lunar facility that uses lunar-derived construction materials as its primary component is a difficult and highly complicated task. The design team chose to simplify this process somewhat by taking a systems integration approach to the problem. This approach emphasizes the articulation of various construction components, how they fit

together, and how they are constructed. Additionally, the facility is seen as the initial application of lunar-derived construction materials to a pressurized structure, a prototypical facility that offers proof of concept. The design team, therefore, concentrated on determining the most effective conceptual approach to constructing pressurized structures on the Moon with emphasis on system flexibility, modularity, simplicity, ease of production, and adaptability to automation.

DESIGN CONSIDERATIONS

Before continuing with a description of the final design concept, it may be useful to briefly discuss some of the design considerations unique to the lunar environment and the effects they may have on the design of basalt structures.

Gravity Level

The most obvious difference between the Moon and the Earth is the gravity level. With the gravity level of the Moon approximately 1/6 that of the Earth, lunar structures will be able to carry a dead load six times the mass of a comparable terrestrial structure. Spans can be increased with a significant savings in construction materials, or, as with pressurized structures, additional regolith for thermal and radiation

protection can be supported. Lunar basalts can be cast in sizes and shapes that will be optimal for lunar construction. Additionally, construction equipment can be downsized because of the lower gravity level, which will offer significant savings in transportation costs.

Radiation Shielding

Protection from the harmful effects of radiation will play an important role in the design of lunar structures. It has been shown that 0.5 meters of lunar regolith is needed to reduce radiation dosages to safe and acceptable levels for short-term stays⁽²⁾. Long-term missions will require additional protection. The lunar basalt structure must be able to support this additional mass in case of depressurization. Definition of high use areas, both pressurized and unpressurized, must be made in order to determine which structures should receive radiation shielding.

Thermal Shielding

In some situations, such as habitats and equipment storage structures, thermal shielding should be provided. Measured temperatures on the lunar surface range between 111°C and -171°C⁽³⁾. Lunar basalt is capable of handling these extremes in temperature without physical or structural degradation.

Vacuum

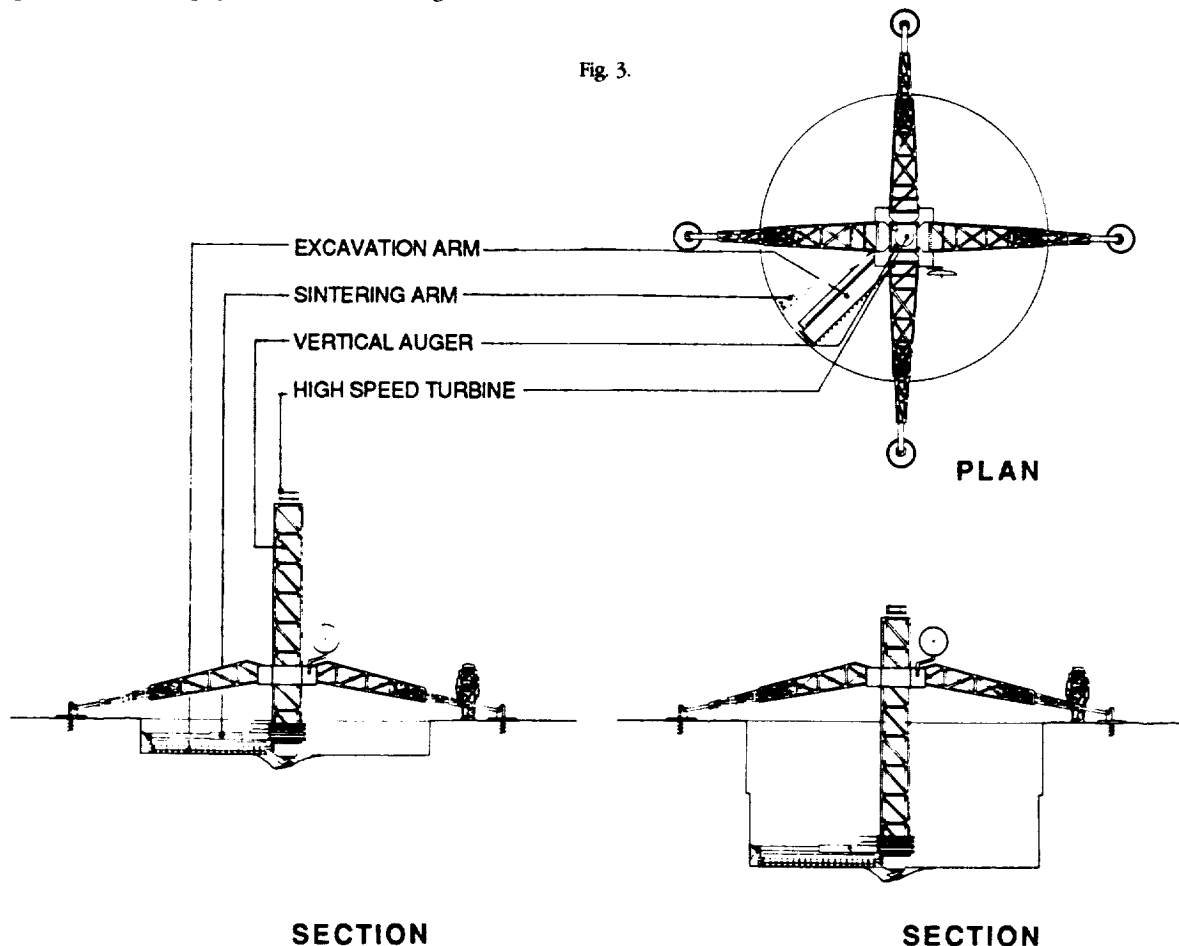
Besides affecting lunar basalt fabrication processes and product strength⁽⁴⁾, vacuum conditions also affect long-term structural properties. Without an atmosphere, the Moon is devoid of most of the harmful effects of terrestrial weathering. This, combined with the fact that basalt is highly resistant to corrosion and abrasion, will give lunar structures extremely long lifespans, and will alleviate many of the problems of continued maintenance.

Lunar Dust

Lunar dust is a highly abrasive, electrostatically charged material. As was shown by the Apollo program, the lunar dust has a negative effect on operations and could present a serious threat to astronaut safety through degradation of equipment and hardware. Cast basalt, because of its high abrasion resistance, is an ideal structural material for the lunar surface.

Automation

Considering the harsh conditions of the lunar surface, automated and teleoperated capabilities will need to be maximized for lunar construction. EVA time will be limited,



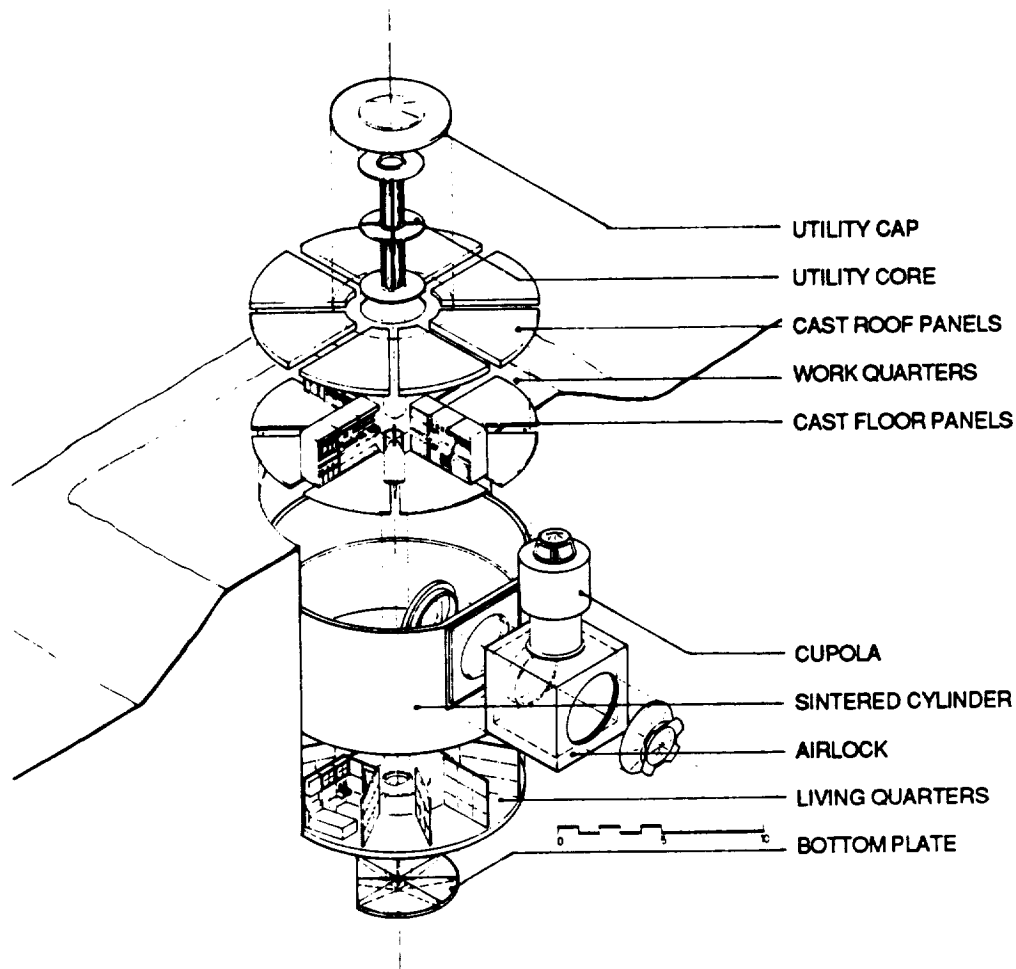


Fig. 4.

therefore expanding the need for robotic and telerobotic construction techniques. Systems should be developed that can easily adapt to different shapes and sizes of lunar basalt materials. In pressurized structures, joints should be minimized to ease assembly and accelerate the construction process. Manufacturing and construction systems should allow for quality control testing of construction materials and joints.

Auxiliary Systems and Interfaces

Auxiliary systems, such as environmental control systems, will need special attach points and interfaces allowing penetration through the structural cavity. There may be a need for modular inserts that can accommodate a number of different systems. Pressurized structures will require additional support around penetrations, increasing the size and mass of the basalt materials.

DESIGN DESCRIPTION

Numerous design concepts were considered before the final solution was realized. These design concepts were classified

into one of three types: monolithic systems, panel systems, or block systems. Monolithic systems, in general, are built-up in a single step process, forming an integral shell-like structure. Block and panel systems, on the other hand, are built from prefabricated pieces, which are then assembled on site, the only difference between the two being the size of their pieces. The final design solution incorporates construction processes from monolithic and panel systems.

The key ingredient of the final design solution is the Regolith Excavation and Sintering Machine (RESM) which, as the name implies, excavates and sinters a cylindrical hole in the lunar surface. Figure 3 shows a plan and two sections of the machine. The RESM's excavation arm first sweeps up the regolith in a circular pattern transferring it to a vertical auger that moves the regolith to the top of the machine where a high speed turbine throws the regolith out and away from the construction site. As the excavation arm continues removal of the regolith, the sintering arm follows closely behind turning the walls of the excavated hole into sintered basalt. The final output of the machine is a cylindrical hole with walls of sintered basalt, 10-15 m in diameter and 6-12 m in depth, depending on the location of the construction site.

The RESM is an easily deployable structure (the legs retract and fold during transport) that has been designed to fit into the cargo bay of the current Space Transportation System. Operation has been automated as much as possible, reducing EVA time and construction expense. Additionally, the RESM, as a primary reusable component of the construction system, significantly reduces continuing construction costs.

Advantages of constructing a subsurface facility are numerous. The surrounding regolith helps to equalize the internal forces of a pressurized structure relieving loads on the shell structure. A subsurface facility also reduces the amount of surface area that must be protected by transferred regolith from cosmic and solar radiation. Regolith that is removed in the construction process is simply piled back on top of the completed structure, alleviating the need for the complicated processes and equipment of above surface protection systems. Additionally, subsurface facilities utilize the regolith *in-situ*, transforming the regolith into a primary building component, which in turn minimizes energy usage and EVA time.

Figure 4 shows an exploded isometric of the completed facility. This cylindrical facility, designed for an unspecified lunar mare site, is 10 m in diameter and 6 m in depth, and consists of 2 floors, the upper configured as work quarters, and the lower as living quarters. The middle floor and roof are comprised of precast, pie-shaped basalt panels that rest on a prepackaged utility core. The utility core, shipped from Earth as a single package, provides the necessary structural rigidity

for the pressurized facility, while allowing complicated utility systems to be packaged as a single unit. Two airlocks are provided (Fig. 4 shows only one for visual clarity) for requirements of dual egress. The airlocks are constructed from six equally sized cast basalt panels to minimize formwork, each containing metal inserts for necessary interfaces, such as hatch doors, etc.

The design team concentrated on a systems approach to the problem. Interior layout and functionality of the presented concept is only one of many possible configurations. Flexibility is a key aspect of the design. Configuration of the interior building systems lends itself to manipulation for changing uses of the facility. Organization around a central utility core maximizes the amount of usable space, and provides a degree of geometric modularity. Modular cast basalt partitions can be used to separate individual crew quarters and work areas, reducing the amount of interior components that must be brought from Earth. Additionally, these interior partitions can be designed and cast to support a variety of attachable fixtures.

Figure 5 shows a section/elevation of the completed facility. Cupolas have been placed above the airlock to allow viewing of the lunar landscape and observation of telerobotic and automated systems. Circulation between floors is provided by a simple ladder, and equipment can be lowered into the first level by a mechanical pulley system. A modular rack system can be used to simplify equipment changeout, much like what is planned for use on the Space Station *Freedom*.

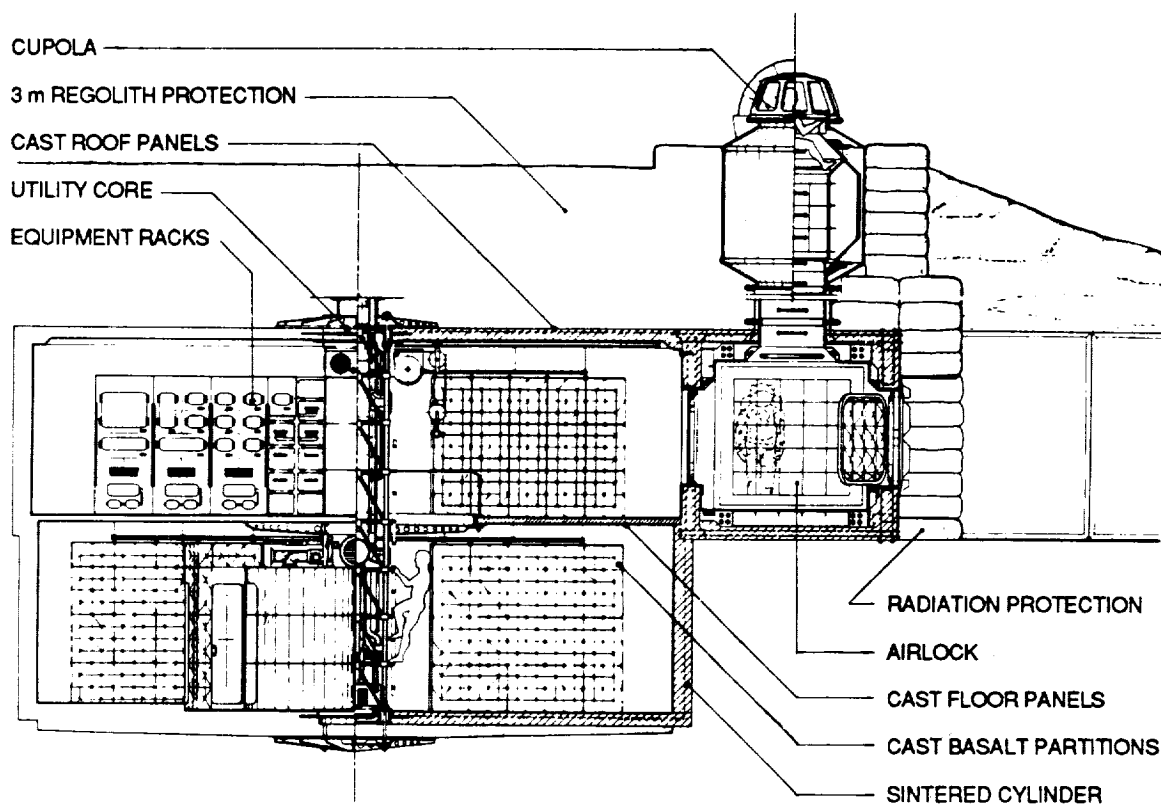


Fig. 5.

FACILITY ASSEMBLY**Step 1**

The first step in the construction of the advanced lunar facility is the digging of trenches for the airlocks. In the final design configuration, these are set at an angle of 180° to each other, allowing minimum distance to egress in emergency situations. Regolith is moved by bulldozing equipment that is already present on the lunar base for mining of oxygen, thus improving the cost efficiency of the equipment and the facility. The cast panels adjacent to the cylinder walls are set in place. This will allow the RESM to structurally integrate the cast panels with the finished sintered walls of the cylinder, forming a monolithic structure, (Fig. 6a).

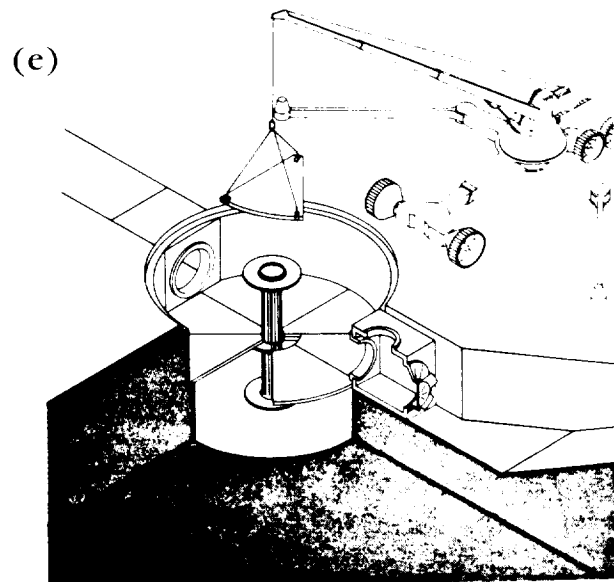
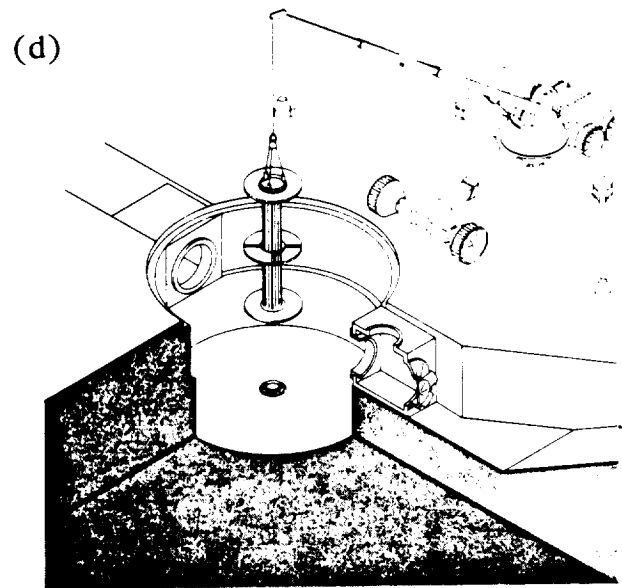
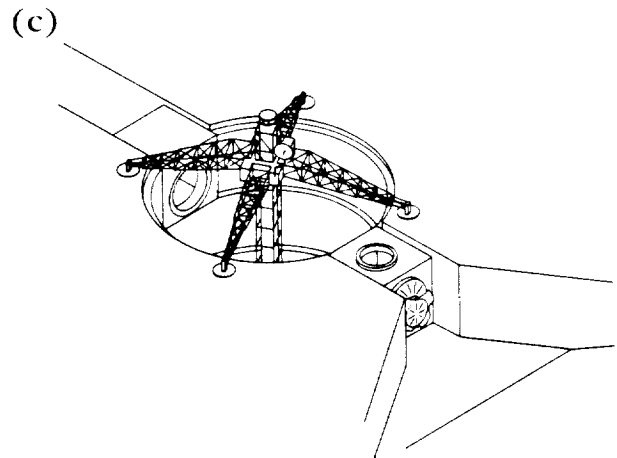
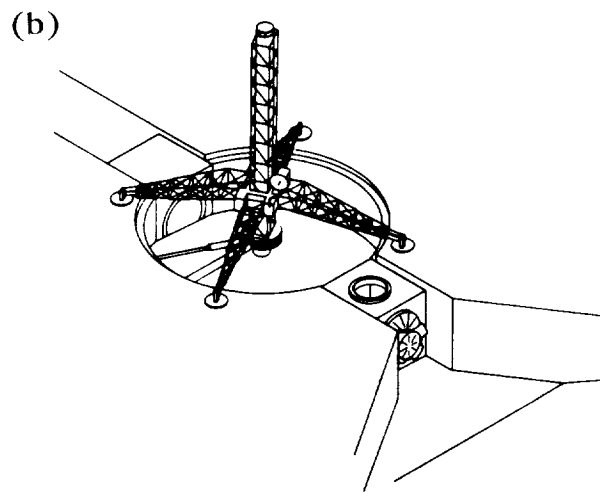
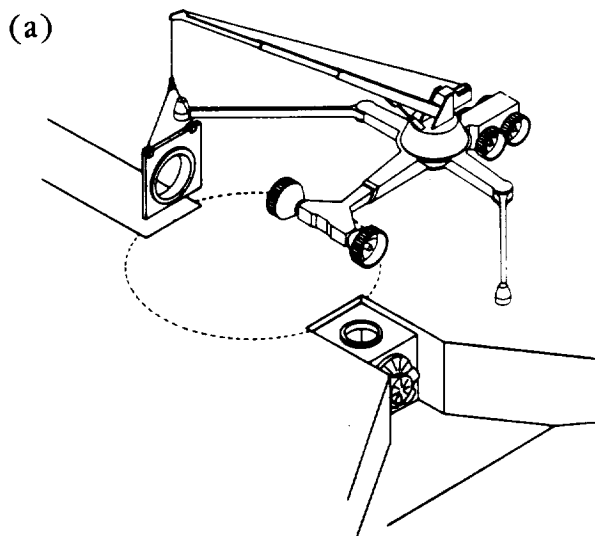
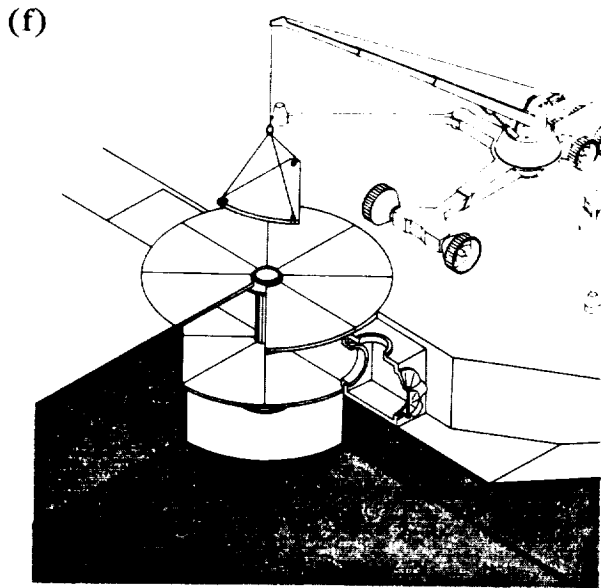


Fig. 6. (a)-(h) Facility Assembly

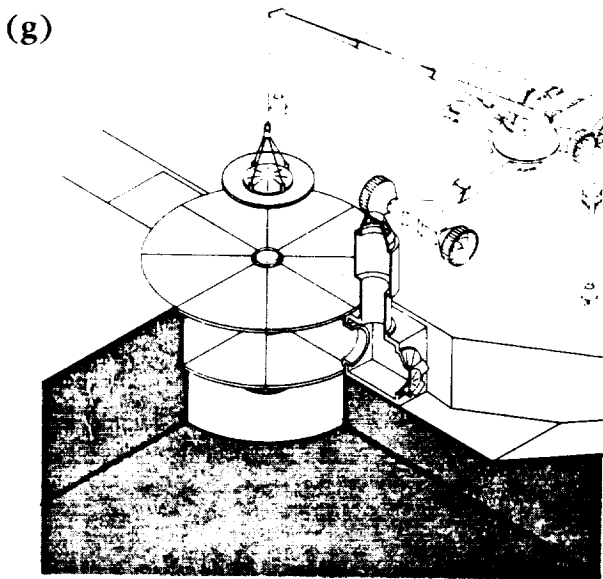


Step 2

The Regolith Excavation and Sintering Machine is lowered into place by the lunar base crane. The legs are unfolded and extended to the proper length, and the excavation and sintering arms are attached. The machine begins the excavation of the cylinder, transferring the removed regolith to the surrounding landscape. The removed regolith will be eventually used to cover the facility for radiation and thermal protection required for human habitats. The sintering arm follows closely behind the excavation arm, applying heat and pressure to the regolith walls forming a 10-20 cm crust of basalt. Ledges are sintered in place, allowing easy placement and support of the cast basalt floor and roof slabs by the lunar base crane (Fig. 6b).

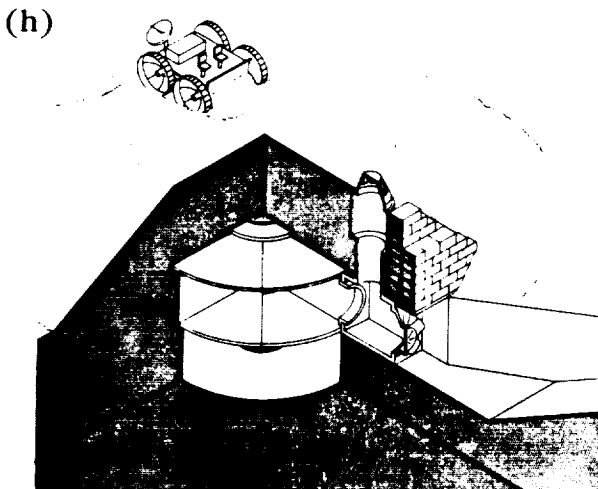
Step 3

Excavation and sintering continues. If a large object is encountered, teeth on the excavation arm simply move the object to a basket located behind the arm. The design team chose a facility depth of 6 m, allowing accommodation of a two-level facility, the upper serving as crew work area and the lower serving as crew living area. After the walls are sintered, a bottom structural plate is buried in the regolith. This plate will serve as an attach point for the utility core. The floor of the cylinder is then sintered, integrating the bottom plate into the monolithic structure. The arms are then detached and brought out of the hole, and the crane moves the RESM to the next construction site (Fig. 6c).



Step 4

Next, the utility core is brought to the site by a lunar utility vehicle, hoisted by the lunar base crane, and lowered into the cylindrical cavity. The utility core is carefully attached to the bottom plate. The utility core, a pre-packaged system brought from Earth, contains all essential systems for the facility, including the life support, air handling, electrical, communications, and heat control systems. The utility core is also a primary component of the facilities structure. The utility core will be wrapped in a protective covering (not shown), keeping the equipment from the damaging effects of lunar dust (Fig. 6d).



Step 5

The middle floor pieces, eight total, are then lowered into place. The floor pieces are made of pie-shaped cast basalt and are set into preconstructed notches in the sintered wall and the utility core. This enables easy installation, requiring minimal EVA time for crane operation. Additionally, the basalt floor pieces are the same size and shape, allowing one metal mold to cast all pieces, thus saving additional transportation costs and eliminating unnecessary waste. The middle floor is separate from the structure enabling, if necessary, the removal of pieces for other interior configurations (Fig. 6e).

Step 6

The cast basalt roof panels are then placed into the preconstructed notches located on the top of the utility core and the side of the sintered cylinder wall. The cast panels contain grooves on abutting edges, which allow the pouring of superheated molten regolith to join the panels together. The superheated regolith partially melts the surrounding cast basalt, fusing the panels together into a single unit, thus allowing the completed facility to act as a monolithic structure. The surrounding regolith helps alleviate much of the stress on the structure, and outward forces on the cylinder top are held in check by the structural integrity of the utility core (Fig. 6f).

Step 7

The utility core and the cylinder top are then capped with a prefabricated metal piece which is the final structural component of the utility core and the lunar facility (Fig. 6g). The observation cupola is also set in place at this time. The cupola, delivered from Earth, will allow for the monitoring of telerobotic systems and the viewing of space and the lunar environment. Exterior viewing will meet some of the psychological needs of the crew and eliminate many of the negative characteristics of subsurface structures. The structure can now be pressurized and interior systems can be delivered and assembled in a shirtsleeve environment. If necessary, an interior vapor barrier can be applied at this time.

Step 8

Covering the facility with regolith is the final step in the assembly process. The regolith, which was excavated from the cylinder, is pushed by a bulldozer over the top of the facility to a depth of at least three meters giving more than adequate protection from both solar and cosmic radiation to the inhabitants below (Fig. 6h). Final assembly and checkout of the interior systems occurs, and the facility is ready for use. Additional facilities can be constructed with the same equipment and the necessary prepackaged systems shipped

from Earth. Other facilities may require less equipment, depending on their function, saving additional transportation cargo space for other needs.

CONCLUSIONS

Lunar resource utilization will play an important and ever-increasing role in the sustainability and growth of a lunar base. After lengthy analysis, the design team determined that basalt, a construction material that can be derived from lunar regolith, will best support the needs of both pressurized and unpressurized structures. The design solution presented in this paper offers a system of simplicity, modularity, and flexibility, achievable in an economic and cost effective manner.

Further research is necessary on basalt structures, in general, and the effects of the lunar environment on basalt processing. Additionally, research must begin on joining techniques, especially between sintered and cast components. Eventually, more accurate studies will need to be conducted on the proper phasing of basalt structures into a lunar base scenario.

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